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8th Int. Symp. "Nanostructures: Physics and Technology"
St Petersburg, Russia, June 19–23, 2000

Low field negative magnetoresistance in double layer structures

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Abstract. The weak localization correction to the conductivity in coupled double layer structures was studied both experimentally and theoretically. The statistics of the closed paths was determined from analysis of the magnetic field and temperature dependencies of the negative magnetoresistance for magnetic field perpendicular and parallel to the structure plane. The comparison of the results with the results of computer simulation of carrier motion at scattering shows that inter-layer tunneling plays decisive role in the weak localization.

The tunneling between 2D layers is one of fundamental features of double layer structures. It changes the quantum corrections to the conductivity, especially in a magnetic field parallel to the 2D plane.

It is well known [1] that the interference of electron waves scattered along closed trajectories in opposite directions (time-reversed paths) produces a negative quantum correction to the conductivity. An external magnetic field, $\mathbf{B} \parallel \mathbf{n}$, where $\mathbf{n}$ is the normal to 2D layer, gives the phase difference between pairs of time-reversed paths which is proportional to the area enclosed ($\varphi = 2\pi \mathbf{BS}/\Phi_0$) and thus destroys the interference. The magnetic field dependence of the negative magnetoresistance is determined by the statistics of the closed paths: the area distribution function, $W(\mathbf{S})$, and area dependence of the average length of closed paths, $\bar{L}(\mathbf{S})$ [2]. Just these functions can be obtained both from the experimental data [3] and from computer simulation of carrier motion at scattering [2].

In a magnetic field parallel to the 2D layer ($\mathbf{B} \perp \mathbf{n}$) the product ($\mathbf{BS}$) is equal zero therefore the magnetic field does not destroy the interference and the negative magnetoresistance is absent in single layer structures for this magnetic field orientation [4].

In coupled double layer structures, the tunneling between layers leads to arising of the closed paths where an electron moves over one layer then over another one and returns to the first one. For this paths the product ($\mathbf{BS}$) in the parallel magnetic field is non-zero and negative magnetoresistance in parallel magnetic field has to appear.

The double well heterostructure GaAs/$In_xGa_{1-x}As$ was grown by Metal Organic Vapor Phase Epitaxy on semi-insulator GaAs substrate. The heterostructure consists of a 0.5 μm-thick undoped GaAs epilayer, a Si δ-layer, a 75 Å spacer, a 100 Å $In_{0.08}Ga_{0.92}As$ well, a 100 Å barrier of undoped GaAs, a 100 Å $In_{0.08}Ga_{0.92}As$ well, a 75 Å spacer, a Si δ-layer and 1000 Å cap layer of undoped GaAs. The measurements were performed in the temperature range 1.5–4.2 K at low magnetic field up to 0.4 T with discrete 10^{-4} T for two orientations: (i) the magnetic field was perpendicular to the structure plane ($\mathbf{B} \parallel \mathbf{z}$), (ii) the magnetic field was parallel to the structure plane and current ($\mathbf{B} \parallel \mathbf{x}$). Additional high field measurements were also made to characterize the structures. The electron densities in the wells have been

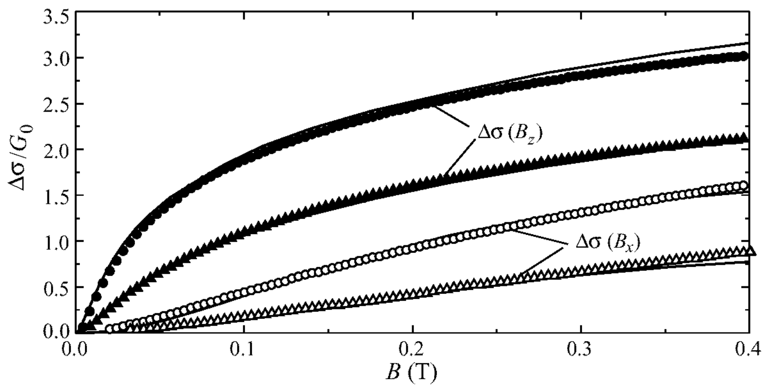

Fig. 1. The magnetoconductivity for two magnetic field orientations for $T = 1.5$ K (circles) and $T = 4.2$ K (triangles). The solid curves are the results of calculation with the inter-layer tunneling probability $t = 0.1$ and $\tau_\varphi = 4.05 \times 10^{-12}$, 1.1×10^{-11} s for $T = 4.2$, 1.5 K, respectively.

determined from the Fourier analysis of the Shubnikov–de Haas oscillations and consist of 4.5×10^{11} cm^{-2} and 5.5×10^{11} cm^{-2}. The Hall mobility was about 5000 cm^2/(V×s).

The magnetic field dependencies of the in-plane magnetoconductivity for magnetic field perpendicular ($\Delta\sigma(B_z)$) and parallel ($\Delta\sigma(B_x)$) to the structure plane are presented in Fig. 1. One can see the negative magnetoresistance is observed for both magnetic field orientations and the effects are comparable in magnitude in contrast to the case of single layer structure. For $B < 0.3$–0.5 T the main contribution to the negative magnetoresistance comes from the interference correction. In this case the magnetic field dependence of the negative magnetoresistance is determined by the statistics of closed paths [5, 2] and for double layer structure it can be written as follows

$$\sigma(B_i) = \sigma_0 + \delta\sigma(B_i) = \sigma_0 - 4\pi l^2 G_0 \int_{-\infty}^{\infty} dS_i\; W(S_i) \exp\left(-\frac{\bar{L}}{l_\varphi}\right) \cos\left(\frac{2\pi B_i S_i}{\Phi_0}\right).$$

Here, $i = x, z$, $G_0 = e^2/(2\pi^2\hbar)$, σ_0 is the classical Drude conductivity, $l = v_F\tau$, $l_\varphi = v_F\tau_\varphi$, v_F is the Fermi velocity, and τ, τ_φ stand for the momentum relaxation and phase breaking time, respectively. The value of $\bar{L}$ is the function of S and l_φ and it was defined by Eq. (6) in Ref. [2]. It should be noted that this expression is valid when the probability to escape the plane at a collision (t) is less than 0.5.

Thus, for the magnetic field perpendicular to the structure plane, $\mathbf{B} = B_z$, the contribution to the magnetoresistance is determined by z-component of $\mathbf{S}$ only and for parallel magnetic field, $\mathbf{B} = B_x$, it is determined by x-component of $\mathbf{S}$.

One can see from the above expression that the Fourier transform of $\delta\sigma(B)/G_0$

$$\Phi(S_i, l_\varphi) = \frac{1}{\Phi_0}\int_{-\infty}^{\infty} dB_i\, \frac{\delta\sigma(B_i)}{G_0} \cos\left(\frac{2\pi B_i S_i}{\Phi_0}\right) = 4\pi l^2 W(S_i) \exp\left(-\frac{\bar{L}}{l_\varphi}\right)$$

carriers an information on $W(S_i)$ and $\bar{L}(S_i, l_\varphi)$. Because the value of l_φ tends to infinity when the temperature tends to zero, the extrapolation of $\Phi(S_i, l_\varphi)$-vs-T curve to $T = 0$ gives the value of $4\pi l^2 W(S_i)$. The $\bar{L}(S_i, l_\varphi)/l_\varphi$ ratio for given S_i can be then obtained as $\ln(4\pi l^2 W(S_i)) - \ln(\Phi(S_i, l_\varphi))$. In more detail this method of analysis of experimental data was described in Ref. [3].

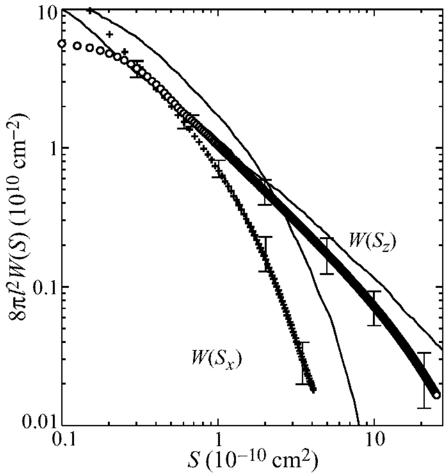

Fig. 2. The experimental (symbols) and calculated (lines) area distribution functions.

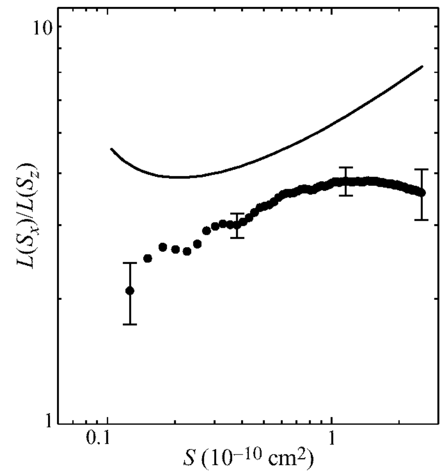

Fig. 3. The experimental (symbols) and calculated (line) area dependence of ratio of the average lengths of closed paths $\bar{L}(S_z)/\bar{L}(S_x)$ for $S_x = S_z$.

The area distribution functions and area dependence of the ratio $\bar{L}(S_x)/\bar{L}(S_z)$ are plotted in Fig. 2 and Fig. 3. The significant difference in $W(S_z)$ and $W(S_x)$ dependencies stands out. The $W(S_x)$ curve shows a much steeper decline at $S_x > (0.8-1) \times 10^{-10}$ cm^2. Other feature of the statistics of the closed paths in double layer structure is the fact that for given S the values of $\bar{L}(S_x)$ are significantly larger than $\bar{L}(S_z)$ (Fig. 3).

Qualitatively these peculiarities of the statistics of closed paths can be understood if one considers how trajectories with large enough length, $L \gg l/t$, look. They are isotropic smeared over XY-plane for the distance $\sim \sqrt{Ll}$ and their extended area in this plane is $s_z \sim Ll$. In YZ-plane they have size $\sim \sqrt{Ll}$ in Y direction and Z_0, where Z_0 is inter-layer distance, in Z direction, so that the extended area in YZ-plane is $s_x \sim Z_0\sqrt{Ll}$. Thus, such trajectories have significantly larger s_z than s_x and the ratio between them increases with increasing S. It is clear that the behaviour of enclosed areas S_z, S_x is analogous and that at $S_x = S_z$, $W(S_z) > W(S_x)$ and the average length of the trajectories $L(S_x)$ is greater than $L(S_z)$.

As was shown in Ref. [2] the area distribution function, the area dependence of average length of closed paths, and the weak localization magnetoresistance can be obtained by the computer simulation of a carrier motion over 2D plane. In our case the model double layer system has been conceived as two identical plains with randomly distributed scattering centers with a given total cross-section. We take into account that after every collision the particle has two possibilities: it transits from one plane to another with a probability t and moves over the second plane or it remains in the plane with probability $(1 - t)$, changing the motion direction only.

The simulation results for the inter-layer transition probability $t = 0.1$ are presented in Figs. 1–3. It is clearly seen that the used theoretical model reproduces all the peculiarities of the experimental data: $W(S_z)$ is close to that obtained experimentally; $W(S_x)$ shows steep decline at large S; and the $\bar{L}(S_x)/\bar{L}(S_z)$ ratio is close to experimental results. In Fig. 1 the calculated magnetoconductance is presented for both magnetic field orientations

for temperatures 1.5 K and 4.2 K. Perfect agreement is evident.

Thus, the results presented show that the inter-layer tunneling plays decisive role in the weak localization in coupled double layer structures.

Acknowledgments

This work is partly supported by RFBR (Grants No 97-02-16168, 98-02-17286) and the Program "Physics of Solid State Nanostructures" (Grant No 97-1091).

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[4] In reality, in a magnetic field parallel to the 2D layer the negative magnetoresistance is observed, but the magnitude of the effect is significantly less. In the structures with one subband filled the effect arises due to asymmetry of the wave function or scattering potential with respect to the center of 2D layer [Vladimir I Fal'ko, J. Phys.: Condens. Matter **2** 3797 (1990)].

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